Passive Filter Aided by Shunt Compensators based on the Conservative Power Theory

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Abstract—Passive filters are widely used in electrical system for power quality improvements. Their first installations date from 1940s and their advantages make them an attractive and standard solution up to nowadays. However, passive filters have their filtering characteristics deteriorated due to parameter variation, caused by aging or temperature. Additionally, a capacitor bank for power factor correction is designed for specific loads and may not supply the right amount of reactive power when loads keep being added or changed. When these issues make the passive filter and the capacitor bank incapable to keep the system operating within acceptable level of power quality, an inconvenience arises and a solution must be provided. A common one is to replace both of them either by new elements or by active power compensators. However, replacing the passive filter and the capacitor bank may not be not economically feasible because they belong to a past investment. This paper presents a solution to overcome such inconvenience keeping the passive filter and the capacitor bank installed and unchanged. It consists of installing two shunt compensators specially designed for performing what the passive filter and the capacitor bank are incapable to do. The result is a reduced processed power in the compensators. The generation of the references is based on Conservative Power Theory. A case study is presented in order to prove the compensators efficacy and the power quality improvement.

Index Terms—active filters, power distribution, power filters, power quality.

I. INTRODUCTION

Power quality in electrical systems has been under concerning for decades. A particular issue involves the harmonic distortion in the line current. Its presence may cause conductor overheating, voltage distortion, transformers malfunctions, unnecessary protection device trip and interference in telecommunication network [1].

Several solutions to improve power quality have been developed. One of the simplest and oldest solutions is the installation of Tuned Passive Filter (TPF) [2]-[6]. TPF makes a low-impedance path at the tuned frequency. Some of the advantages of using TPF are the low-initial cost and the robustness. However, the filtering efficacy may be deteriorated due to parameter variation caused by aging or temperature.

Regarding the improvement of power factor correction for sinusoidal conditions, capacitor banks are used due to their low cost and design simplicity. Nevertheless, a capacitor bank is designed for specific amount of loads and once the loads are constantly being added or removed, its performance may be backward and the power quality deteriorated. Switched capacitors appear as a solution for load variation, but the switch-on and off transitory behaviors are very severe to the grid [7]. Additionally, if the load has low displacement factor (phase difference between fundamental frequency current and voltage), the TPF capacitive behavior at this frequency can even reduce the power factor.

The technological advancement allowed solutions with more accuracy and efficiency [8]-[11], such as active compensators. These compensators can be designed to replace the passive filters and capacitor banks. However, replacing them is not economically feasible because they belong to a past investment. Therefore, an attractive solution is to keep installed the passive elements and to install an active compensator, resulting in a hybrid structure.

The processed power of an active compensator is proportional to its output current. When a passive filter is fully replaced by an active compensator, the last should be sized to hold all the current which was circulating through the passive filter. On the other hand, when a shunt compensator is installed and the passive filter is kept unchanged, the compensator is sized only to hold the current which is incapable to circulate in the passive filter. Since the output current is lower in this case, the processed power is expected to be lower. Similar analysis can be found in capacitor banks.

This paper proposed two shunt compensators to aid a TPF and a capacitor bank. The TPF and the capacitor bank are kept installed and unchanged. The compensators commands are defined based on the Conservative Power Theory (CPT) [12]-[15]. One is designed to compensate TPF detuning and also to mitigate harmonic current that is beyond the TPF bandwidth while the other is to compensate reactive power which is not compensated by the capacitor bank, either by ageing or connection of new loads. Since the proposed solution keeps the TPF and the capacitor bank, the compensator output current is expected to be reduced as well as the its cost.

II. ELECTRICAL SYSTEM PERSPECTIVE

Fig. 1 presents a simplified diagram of a typical electrical system. It consists of the main generation, distribution transformers and two PCCs. There is a TPF tuned at 5th harmonic, a capacitor bank and linear and non-linear loads. The utility and transformer impedance will be later represented by an equivalent RL circuit. The non-linear load is a six-pulse three-phase thyristor rectifier.

The 5th load harmonic current harmonics is deviated by the passive filter branch, composed by C5 and L5.

In accordance to the IEEE1531-2003 recommendation [16], the TPF should not be tuned exactly at the harmonic frequency. Instead, it is recommended a lower value to avoid the excitation of the series resonance by source voltage harmonics. But the lower the tuned frequency is, the lesser effective the TPF is.
III. CPT BASED COMPENSATORS

There are two compensators to support the electrical system: (i) C1, connected at the PCC1, where the capacitor bank is installed, and (ii) C2, connected at the PCC2, where the TPF is connected. Fig. 2 presents a similar system diagram showing the two proposed compensator. They are represented by dependent current sources. It is also presented the variable which must be measured in order to obtain the compensator current references.

A. The Conservative Power Theory

The CPT is a time-domain theory applicable to any periodic signal, single- or poli-phase system with or without neutral conductor. The principle operation is the orthogonal decomposition of electrical variables, resulting electrical quantities with physical meaning. Each quantity represents electrical load characteristics like consumed active power, storage energy, phase displacement between voltage and current, unbalancing and so on. Moreover, the CPT does not make variable transformation.

The CPT is used in this paper to compute electrical quantities at the PCC1 and PCC2. The active and reactive powers, the harmonic content and the unbalance information of them are extracted by means of the CPT. Later, the compensators 1 and 2 use these quantities to compose their current reference signals.

The following analysis is in a single-phase based but it is applicable to three-phase.

The average value of a variable \( x \) is given by (1).

\[
\bar{x} = \frac{1}{T} \int_{0}^{T} x(t) \, dt
\]  

The time-integral of a variable \( x \) is given by (1).

\[
x(t) = \frac{1}{T} \int_{0}^{T} x(\tau) \, d\tau
\]  

The unbiased integral of a variable \( x \) is given by (3).

\[
\hat{x}(t) = x(t) - \bar{x}(t)
\]  

Where the second term of (3) is the average value of (2). The unbiased term means the integral does not contain average value.

The time-derivative of a variable \( x \) is given by (4).

\[
\ddot{x}(t) = \frac{dx(t)}{dt}
\]  

The unbiased integral and the time-derivative present the following properties:

\[
\langle \dot{\hat{x}}, \hat{x} \rangle = \langle \hat{x}, \dot{\hat{x}} \rangle = 0
\]  

\[
\langle \dot{\hat{x}}, \dot{y} \rangle = -\langle \hat{x}, y \rangle
\]  

\[
\langle \dot{x}, \dot{y} \rangle = -\langle \dot{x}, y \rangle
\]  

\[
\langle \hat{x}, \dot{y} \rangle = -\langle x, y \rangle
\]  

where \( \langle \cdot, \cdot \rangle \) is the internal product.

The root-mean square (RMS) value of a variable \( x \) is
represented by (6)

$$X_{mv} = \|x\|$$  \hspace{1cm} (6)

For a given voltage $v(t)$ and a current $i(t)$, the active current for one phase is given by (7).

$$i_a = \frac{\langle v_x, i \rangle}{\|v_x\|^2} v$$  \hspace{1cm} (7)

In a similar way, the reactive current for one phase is given by (8).

$$i_r = \frac{\langle \hat{v}_i, i \rangle}{\|\hat{v}_i\|^2} \hat{v}$$  \hspace{1cm} (8)

The void current is given by (9).

$$i_v = i - i_a - i_r$$  \hspace{1cm} (9)

The void current contains all quantities that do not present neither active nor reactive behavior.

The three-phase active current is given by (10).

$$i_{active(a,b,c)} = \frac{\langle \hat{v}_{a,b,c}, i_{a,b,c} \rangle}{\|\hat{v}_{a,b,c}\|^2} v_{a,b,c}$$  \hspace{1cm} (10)

The three-phase reactive current is given by (11).

$$i_{r(a,b,c)} = \frac{\langle \hat{v}_{a,b,c}, i_{a,b,c} \rangle}{\|\hat{v}_{a,b,c}\|^2} v_{a,b,c}$$  \hspace{1cm} (11)

The three-phase void current is given by (12).

$$i_{v(a,b,c)} = i - i_{active(a,b,c)} - i_{r(a,b,c)}$$  \hspace{1cm} (12)

The three-phase active balanced current is given by (13).

$$i_{activebal(a,b,c)} = \frac{\langle \hat{v}_{a,b,c}, i_{a,b,c} \rangle}{\|\hat{v}_{a,b,c}\|^2} v_{a,b,c}$$  \hspace{1cm} (13)

The three-phase reactive balanced current is given by (14).

$$i_{bal(a,b,c)} = \frac{\langle \hat{v}_{a,b,c}, i_{a,b,c} \rangle}{\|\hat{v}_{a,b,c}\|^2} v_{a,b,c}$$  \hspace{1cm} (14)

For balance compensation, it is sufficient to add to the compensator current reference the equations (13) and (14).

**B. Set-point for Current Compensators**

The compensator current reference is computed based on the previous equations. Once the compensator C2 is designed to mitigate the harmonic currents not compensated by the TPF, its current reference is the PCC2 void current. Therefore, the C2 current reference is given by (15).

$$i_{c2}^* = i_{v,pcc2}$$  \hspace{1cm} (15)

Similarly, the compensator C1 is designed to consider only the reactive energy, its current reference is given by (11).

$$i_{c1}^* = i_{r,pcc1}$$  \hspace{1cm} (16)

Since the compensators follow their current reference, the power quality in the system will be improved.

**IV. CASE STUDY**

The system presented in Fig. 2 was simulated in PSIM in order to verify the proposed compensators efficacy. Initially, the compensators are turned off and the system is in steady-state condition. The switch S1 and S2 are opened. Tab. I presents the system parameters used in simulation. The TPF C5 and L5 is tuned at 5.1th harmonic in order to emulate a detuning caused by ageing.

**TABLE I. SYSTEM PARAMETERS USED IN THE SIMULATION**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_g$</td>
<td>Main Generation RMS voltage</td>
<td>69 kV</td>
</tr>
<tr>
<td>$V_{pcc1}$</td>
<td>PCC1 RMS voltage</td>
<td>13.8 kV</td>
</tr>
<tr>
<td>$V_{pcc2}$</td>
<td>PCC2 RMS Voltage</td>
<td>480 V</td>
</tr>
<tr>
<td>$f_s$</td>
<td>Frequency of the system</td>
<td>60 Hz</td>
</tr>
<tr>
<td>$I_l$</td>
<td>Maximum demand load current</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(fundamental frequency component)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>at PCC1</td>
<td></td>
</tr>
<tr>
<td>$S_{bank}$</td>
<td>Capacitor bank Apparent Power</td>
<td>50 kVA</td>
</tr>
<tr>
<td>$I_{dc}$</td>
<td>Rectifier DC Load Current</td>
<td>200 A</td>
</tr>
<tr>
<td>$C_5$</td>
<td>Tuned Passive Filter Capacitor</td>
<td>300 uF</td>
</tr>
<tr>
<td>$L_5$</td>
<td>Tuned Passive Filter Inductor</td>
<td>960 uH</td>
</tr>
</tbody>
</table>

Fig. 3 presents the PCC2 three-phase current when the compensator C2 is turned on, at $t = 5$ s. After that, the PCC2 current became sinusoidal. The spikes are due to the high current derivative caused by the non-linear load. The PCC2 current THD before and after the compensator began to operate are 20.9% and 9.0%.

Fig. 4 depicts the TPF and the compensator C2 current for one phase when the compensator is turned ON. The C2 begins to operate with no oscillating behavior and the TPF current is kept unchanged.

![Fig. 3. PCC2 three-phase current when the compensator C2 is turned ON.](image-url)
Fig. 4 portrays the current spectra for PCC2, non-linear load, TPF and compensator C2 currents. The fundamental components were overlapped for better visualization of the remaining spectra. The non-linear load (Inl) presents a high harmonic content. The TPF (I5a) presents only the fundamental and 5th harmonic components. The filtered 5th harmonic component is approximately 50% of the load 5th harmonic current due to the detuning. The compensator C2 current (IC2) contains the remaining 5th harmonic and does not contain fundamental component. Moreover, the compensator C2 current presents all other harmonics equal to the non-linear load. The residual components in the PCC2 current are due to non-ideal current divisor formed by the PCC2 and TPF impedances. Notice that without the installation of C2, the 5th harmonic of the PCC2 current would be the difference between the nonlinear load and the TPF, at 5th harmonic. Moreover, all the remaining harmonics generated by the nonlinear load would circulate through the PCC2 point upstream.

Fig. 5 presents the spectra content for the IEEE519-2014 [17] limit, the nonlinear load (Irect), the PCC2 current when only the TPF is installed (Ipcc2_TPF) as well as the PCC2 current when the C2 is installed (Ipcc2_TPF+C2). The fundamental components were omitted for better visualization. The nonlinear load current components violated the IEEE519-2014 levels in all analyzed harmonics, except the 11th. When just the TPF is installed as a solution, the 5th and the 11th are lower than the limit allowed by the IEEE519-2014. On the other hand, when the C2 is installed, all harmonic components in the PCC2 current are within the specified limit. The harmonic content for the PCC1 current is not presented because such current is free of distortion.

Fig. 6 shows the PCC2 current, the nonlinear current, the TPF current and the compensator C2 current when switch S1 turns-on. Neither oscillatory nor unpredictable behavior happened in the measured variable.
voltage and current to be in phase. It is important to highlight the fact that the most part of the PCC1 reactive energy is being compensated by the capacitor bank. The spikes found in the PCC1 current are lower those found in PCC2 current because the capacitor bank acts as a high-pass filter. If the C1 was not installed, the PCC1 would operate with displacement factor different from one, contributing to the stress of the distribution transformer.

Fig. 8. The PCC1 current and voltage for phase A when the compensator C1 is turned ON.

Fig. 9 shows the PCC1 current and voltage for phase A in an occurrence of a capacitor bank fail. At t = 5.24 s the capacitor bank is permanently disconnected and the compensator C1 begins to compensate all the PCC1 reactive power. The steady-state is reached after one cycle and half. The compensator C1 current is sinusoidal and it is 90 degree phase-shifted related to the PCC1 voltage, indicating that compensator processes only reactive energy.

Fig. 9. The PCC1 current and voltage for phase A in an occurrence of a capacitor bank fail.

Fig. 10 presents the PCC2 current when C2 is compensating the unbalanced load.

Fig. 10. The PCC2 current when C2 is compensating the unbalanced load.

V. DISCUSSION ABOUT THE COMPENSATORS

In order to analyse the compensation strategy, the compensators are represented by controlled current sources in Fig. 2. Nevertheless, in real applications they are power electronic converters.

Regarding the output current, the compensator 1 deals with only fundamental component while the compensator 2 with fundamental and harmonics. The fundamental is exclusively for reactive power compensation.

As the compensator 1 is installed at 13.8kV bus, one possible topology is the symmetrical multilevel inverter topology [18]-[20]. By using phase-shift modulation each cell of the multilevel inverter can operate at low frequency (some hundreds of Hz), according to the characteristics of the power switches, while the total synthesized voltage switching frequency is the individual cell commutation frequency multiplied by the number of cells. This way a high quality, low distortion fundamental component is produced [21]-[22]. Such behaviour allows the application of a current controller with relative high bandwidth, a necessary condition to make the current to follow its reference with negligible steady-state error.

On the other hand, the compensator 2 is installed in low voltage. Therefore, the compensator 2 may have the classical H-bridge topology with high frequency Pulse-Width Modulation (PWM) [23]. The harmonic characteristic of the compensator 2 presents all harmonic spectrum of the nonlinear load, limited to compensator output filter bandwidth. In the presence of TPF, the respective harmonic components will flow through the TPF, reducing the compensator processed power.
VI. COST CONSIDERATIONS

The quantity to represent the life-cycle cost of a system is defined as the total Net Present Cost (NPC) which includes all costs and revenues that occur within the project lifetime, with future cash flows discounted to the present. Whereas the simulation process models a particular system configuration, the optimization process determines the best possible system configuration. In a system like the one in this paper, the “optimal” system configuration is the one that satisfies the user-specified constraints at the lowest total NPC. In order to find the optimal system configuration, one may involve deciding on the mix of components that the system should contain, the size or quantity of each component, and the cycling strategy the system should use. Possible decision variables (DV) might be:

DV01 - Cost of large capacitive power requirements at fundamental frequency,

DV02 - Power dissipated (and lost for revenues) in the TPF and any damping,

DV03 - Investments to overcome for physical restrictions of installing components, particularly civil constructions and permits. The key physical properties of the study might be their nominal current, its capacity curve, its lifetime curve, its minimum load, and its round trip efficiency. The cost of purchasing power from the grid can comprise an energy charge based on the amount of energy purchased in a billing period, and a demand charge based on the peak demand within the billing period. The converter size, which is a decision variable, refers to the inverter capacity, meaning the nominal output current. The economic properties of the converter are its capital and replacement cost, its annual Operations & Maintenance (O&M) cost per year, and its expected lifetime in years.

Optimization can help the modeler find the optimal system configuration out of many possibilities. Consider, for example, the task of retrofitting the shunt compensators described in this paper. In analyzing the options for redesigning the system, the modeler may want to consider the arrangement of components, but would not know in advance what combination of DV01, DV02 and DV03 above will minimize the life-cycle cost. These three variables would therefore be decision variables in this analysis.

A What-IF case study can be implemented with those variables, and many more that might be important for the life-cycle cost study, for example by allowing parameters such as the number or size of each component, the total capital cost of the system, the total net present cost, the leveled cost of energy (cost per kWh), the annual power consumption for each solution, and the number of hours the maintenance will make the system not operational per year.

A variable for which the user has entered multiple values is called a sensitivity variable. Each combination of sensitivity variable values defines a different sensitivity case. For example, if the user specifies six values for the (i) cost of large capacitive power requirements, (ii) power dissipated (and lost for revenues) in the TPF and three values for investments to overcome for physical restrictions of installing components, the total number of cases is 6x6x2 = 72 for sensitivity analysis in dealing with uncertainty in the optimal decision. With a careful spreadsheet evaluation, a modeler can make informed decisions despite uncertainty in important variables.

The proposed compensator can have renewable or non-renewable technology as primary source. Renewable and non-renewable energy sources typically have dramatically different cost characteristics. Renewable sources tend to have high initial capital costs and low operating costs, whereas conventional non-renewable sources tend to have low capital and high operating costs. In a full optimization process, the modeler must compare the economics of a wide range of system configurations comprising varying amounts of renewable and non-renewable energy sources. To be equitable, such comparisons must account for both capital and operating costs.

Life-cycle cost analysis does that by including all costs that occur within the life span of the system. The total NPC condenses all the costs and revenues that occur within the project lifetime into one lump sum in today’s dollars, with future cash flows discounted back to the present using the discount rate. The modeler specifies the discount rate and the project lifetime. The NPC includes the costs of initial construction, component replacements, maintenance, fuel, plus the cost of buying power from the grid and miscellaneous costs such as penalties resulting from pollutant emissions. Revenues include income from selling power to the grid, plus any salvage value that occurs at the end of the project lifetime.

With the NPC, costs are positive and revenues are negative. This is the opposite of the net present value. As a result, the NPC is different from net present value only in sign. All prices escalate at the same rate over the project lifetime. With that assumption, inflation can be factored out of the analysis simply by using the real (inflation-adjusted) interest rate rather than the nominal interest rate when discounting future cash flows to the present. The modeler must use the real interest rate, which is roughly equal to the nominal interest rate minus the inflation rate. For each component of the system, the modeler specifies the initial capital cost, which occurs in year zero, the replacement cost, which occurs each time the component needs replacement at the end of its lifetime, and the O&M cost which occurs each year of the project lifetime.

VII. ACKNOWLEDGMENTS

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VIII. CONCLUSIONS

This paper proposed two shunt compensators to aid a TPF and a capacitor bank. The TPF and the capacitor bank are kept installed and unchanged. The calculation of the current references for the compensators is based on the Conservative Power Theory. One compensator was designed to compensate harmonic current produced by non-linear loads and to compensate the loss of filtering efficacy due to the TPF parameter variation. The other compensator was designed to compensate reactive energy and load unbalance.

A case study was performed to verify the efficacy of the compensators. According to the results, the power quality was improved and no unpredictable behavior occurred in the system during step load and element disconnections. The compensators operated in combination with the tuned passive filter and the capacitor bank.

The proposed solution kept unchanged the already existent passive filters, once they are a past investment and removing them would not be good economics or a practice that the utility could implement. The case study demonstrates that the compensators process lower power compared to solutions in which passive filters are totally removed. Therefore, the compensator sizing and cost are reduced, making the proposed solution an attractive implementation for power quality enhancements with relative reduced costs. The simulation file used in this paper is freely available on https://sites.google.com/site/busarellosmartgrid/home.

REFERENCES